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14. ABSTRACT
Seabed-structure interactions are responsible for the burial of heavy objects, such as mines, pipelines, concrete breakwaters, platforms, debris, and other objects on the seafloor. In low shear strength muds, these objects are known to bury at impact or to sink into the sediment if the buoyant weight of the object exceeds the bearing capacity of the seafloor. In higher energy sandy sediments, burial by scour and fill, momentary or cyclic wave-induced liquefaction, and seabed morphological changes (e.g., transverse bedform migration, changes in shore-rise and bar-berm conditions, sediment deposition) is common. Each of the possible burial processes will be discussed and an integrated, time-dependent object burial model is proposed. Results from six recent burial experiments using instrumented mines are used to document burial at impact and subsequent burial by biological processes, scour and fill, changes in near-shore bar morphology, liquefaction, and subaqueous dune migration.

15. SUBJECT TERMS
seafloor, mine burial, seabed-structure interactions, scour, momentary wave-induced liquefaction, cyclic wave-induced liquefaction, seabed morphological changes, shore-rise, bar-berm, subaqueous dune migration

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NRL Mine Burial Experiments

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Abstract: Seabed-structure interactions are responsible for the burial of heavy objects, such as mines, pipelines, concrete breakwaters, platforms, debris, and other objects on the seafloor. In low shear strength muds, these objects are known to bury at impact or to sink into the sediment if the buoyant weight of the object exceeds the bearing capacity of the seafloor. In higher energy sandy sediments, burial by scour and fill, momentary or cyclic wave-induced liquefaction, and seabed morphological changes (e.g., transverse bedform migration, changes in shore-rise and bar-berm conditions, sediment deposition) is common. Each of the possible burial processes will be discussed and an integrated, time-dependent object burial model is proposed. Results from six recent burial experiments using instrumented mines are used to document burial at impact and subsequent burial by biological processes, scour and fill, changes in near-shore bar morphology, liquefaction, and subaqueous dune migration.

Introduction

Buried mine detection has been and is still one of the greatest threats facing Shallow Water Mine CounterMeasures (SWMCM) operations (Richardson and Tooma, 1993; Lott, 2000). The possible presence of buried mines can change MCM tactics from one of mine hunting to one of minesweeping or area avoidance. The ability to predict mine burial both for planning and during operations (strategic and tactical scenarios) is therefore of great importance to Naval forces. Processes known to contribute to mine burial include burial at impact usually in low strength muddy sediments; scour and fill; bedform migration or transverse bedform movement; bedform morphological alterations, such as changes to shorerise or bar-berm conditions; liquefaction or fluidization of the sediment; and biological processes that scour or alter seafloor roughness or sediment physical properties.

We first present the framework for a new, integrated, time-dependent, mine burial prediction model useful for both a) long-term burial prediction based on historical databases and fleet numerical meteorological and oceanography prediction models and b) real-time, in-stride mine burial prediction based on updates with environmental measurements made with systems organic to fleet assets. The results of six mine burial experiments using newly developed instrumented mines are then used to demonstrate burial at impact and subsequent burial by biological processes, scour/fill and changes in nearshore beach and bar morphology, and subaqueous dune migration. In depth analyses of mine burial process and/or validation of specific mine burial models are beyond the scope of this introductory paper. The emphasis is instead on the development and uses of instrumented mines as a tool for measuring mine burial.

An Integrated Mine Burial Model

NRL has developed the framework for a new mine burial model (Fig. 1), based on an extensive review of the mine/object burial literature (Lott, 2000), participation in Mine Burial Specialist Team (NATO Subgroup 31; January 1995 – December 1998) meetings, and experiments in the North Sea (Anonymous, 1999). This model recognizes that mine or object burial is time dependent and that burial processes are not independent. Time dependent mine burial is predicted from numerical oceanographic models or in situ measurements of wave climate and tidal and storm-induced bottom currents; sediment physical properties and small-scale morphological features measured in situ or compiled in historical databases; and characteristics of the mine threat based on intelligence. The model provides both strategic and tactical mine burial prediction.

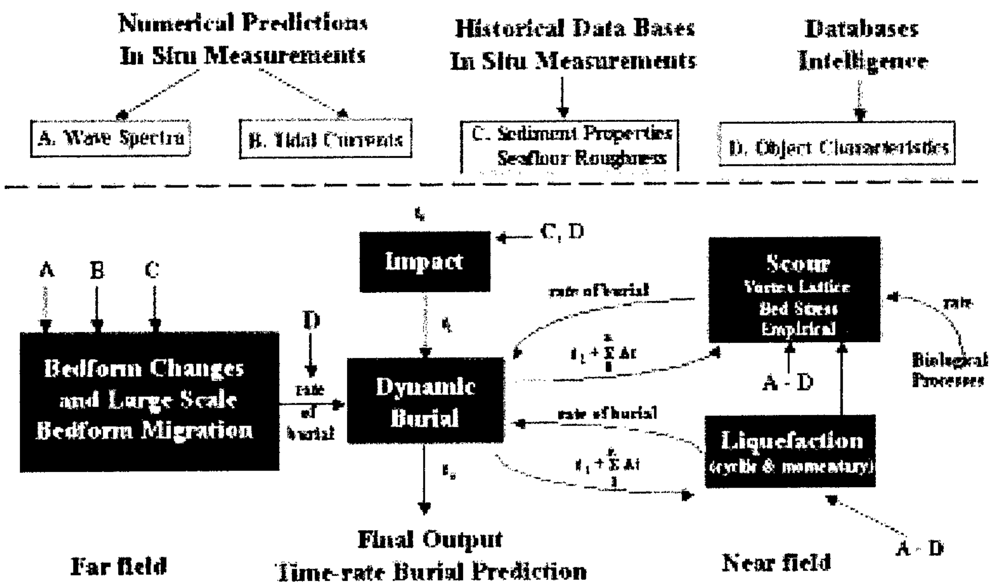

Figure 1. Flowchart for an integrated mine burial model

The impact burial model, first proposed by Arnone and Bowen (1980) and most recently modified by Hurst (1992), is probably the most widely used, physically sound, and extensively tested of the mine burial models. The model provides a time history of mine movement based on forces and torques on a cylindrical mine as it falls through air, water, and embeds in the sediment. Environmental inputs (gradients of sediment bulk density and shear strength) together with mine characteristics (D) are used to predict burial of cylindrical-shaped or tapered mines. Sediment shear strength and bulk density gradients are typically based on core samples, in situ penetrometers, or acoustic sediment classification systems. As we will show in this paper several issues exist relative to the movement of the mine through the water column.

Both near-field and far-field processes can further bury objects in the seafloor. Far-field morphological changes of the seafloor are unaffected by the presence of mines, and mine characteristics (D) are only considered as part of the geometric aspects of burial. A great variety of seabed features can be found in estuaries, beaches, and shallow coastal regions. Many of these features are in equilibrium with modern hydrodynamic conditions (e.g. not relict) and their size, location, and morphology over time can be predicted from measured or predicted oceanographic conditions (A & B) and seafloor properties (C). Several geometric models have been proposed to predict mine burial by migrating sand dunes (Mulhearn, 1996). These models require information on dune dimensions and migration rates, which can be measured directly or predicted using sediment transport models (see Soulsby, 1997). Changes in equilibrium beach profiles, especially the movement of offshore bars, can also be predicted from values of sediment properties and wave climate. Changes in these beach profiles are related to either seasonal changes in wave climates (Inman et al., 1993) or to the effects of major storms (Lee et al., 1998).

Near-field burial processes (scour and fill, liquefaction, and biological processes) are all affected by the presence of the mine. Scour, caused by turbulent flow around mines under the influence of oscillatory waves, currents, and tides, has been modeled by a variety of empirical and physics-based models. Many of these scour models are based on the empirical formulations developed for bedload and suspended load sediment transport around cylinders and are based on the laboratory flume studies of Carstens and Martins (1963). Other models simply add an enhancement factor to standard sediment transport models (bed shear stress required to initiate bedload and suspended load transport from tidal and wave-induced currents) to account for the added turbulence caused by the mine's presence (see Whitehouse, 1998). Inman and Jenkins (1996) developed a more sophisticated scour model to account for burial of mines by scour and changes in beach profiles. Turbulent flow around an arbitrary mine shape on the seafloor is modeled as horseshoe-shaped bound and trailing vortices initiating from the mine shape. The summed velocity field resulting from these vortices is used to calculate scour around the mine. The model accommodates a variety of mine shapes, provides time-stepped scour for varying flows, provides motion equations to allow prediction of mine movement during burial, and allows for seasonal changes in the beach profile. In general, scour and fill burial models require a time history of near bottom currents (based on tidal or wind-driven currents), surface gravity wave spectrum, sediment grain size and bulk density, seafloor morphology, and mine characteristics as model inputs. Liquefaction/fluidization of the seafloor can occur by momentary or cyclic liquefaction (Brandes, 1999; Mulhearn, 1998). In either case when the build-up of excess pore pressure within the sediments exceeds the vertical effective stress of the cohesionless sediments (which results from the self-weight of the grains), sediments lose their shear strength or bearing capacity and the mines sink based on their buoyancy in the liquefied sediment. Burial by liquefaction is a controversial topic and numerous momentary and cyclic liquefaction models exist but none have been validated by adequate field experiments. Biological processes can physically both scour and infill around mines. Objects such as mines are known to attract a variety of larger benthic and pelagic animals by providing food and habitat. The activities of these animals can change seafloor physical properties as well as microtopographic roughness near a mine. Depending on the activities sediment transport can be either accelerated or retarded.

The Instrumented Mine

One of the major problems in the experimental validation of mine burial models is the difficulty of continuous measurement of the behavior of the mine. In past experiments, qualitative observations by divers were limited to 1-2 times a day and then only during good weather conditions. Burial is an episodic behavior often triggered by storms or strong tidal currents. Divers rarely observe either mine movements or the actual burial process but instead observe the end conditions. Laboratory experiments have difficulties related to scale, especially concerning sediment grain size, surface gravity wave height and period, bedform size, and mine shape, size and weight. The instrumented mine provides a tool for continuous monitoring of the movement of the mine (heading, pitch and roll) as well as the percentage of the surface area of the mine actually buried. The NRL design is based on an instrumented mine developed by Ingo Stender of Forschungsanstalt der Bundeswehr für Wasserschall- und Geophysik in Kiel, Germany. Heading ($\pm$ 1°) is measured with three solid-state compasses and roll and pitch ($\pm$ 1°) of the mine are measured with a three-axis accelerometer. Burial is measured by three rings of paired optical sensors externally mounted at 15° intervals around the mine. Transmitting optical sensors are LED's and receiving sensors are phototransistors. Burial is measured by blockage between these sensors. The mine in Figure 2 is made of aluminum and is 1.5 m long and 0.47 m in diameter. The weight in air is 619 kg and in water is 357 kg but these weights are adjustable. During the experiments described below, measurements were made every 30 minutes and stored on an internal 1-Gbyte hard drive. Given the power requirements and battery capacity, measurements (rates are programmable) can be made every 30 minutes for 90 days. Modifications to the mine for impact burial experiments included addition of a 2^{nd} set of 4-g three axis accelerometers, a 25-g accelerometer to record higher energy impact with the air-water interface and the seafloor, disconnecting the optical sensors, and increasing the data collection rate to 300 Hz.

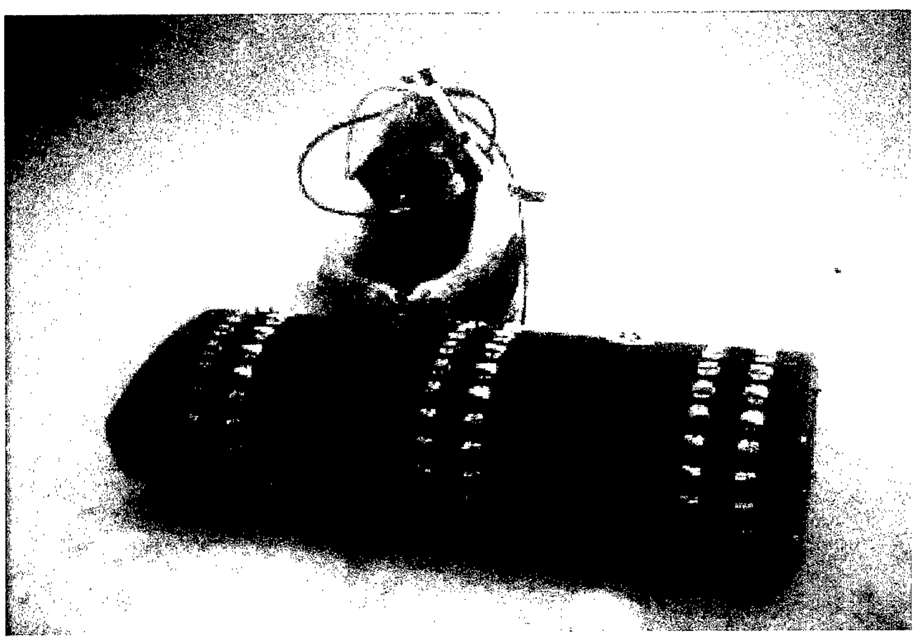

Figure 2. The NRL instrumented mine being deployed in the East Pass of the Destin Inlet, northeastern Gulf of Mexico (Photograph by Ricky Ray).

Mine Burial Experiments

Panama City: A successful functional test of the instrumented mine was conducted in 7-m water depth on a sandy substrate off Panama City, Florida 10-25 June 1999. The mine was gently lowered to the sediment surface, a well sorted, fine sand (0.25 mm mean diameter) with 39% porosity and 2024 kg m^{-3} bulk density. Changes in depth of burial of the mine over the 15-day period were minimal. The line-of-sight between sets of optical sensors 11-14 was broken by the presence of sand during most of the deployment (Fig. 3). These 4 optical sensors transcribe an arc of 60° in contact with the sandy sediment, representing a 7% depth of burial. Changes in apparent burial from 10-22 June are probably a result of scour by fish and blue crabs (Fig. 4). This construction of scour pits is related to feeding or securing habitat or refuge from predation. The front (1) and middle (2) rings were subject to apparent burial (90° arc or 14% burial) 22-24 June. Divers observed small mounds of sediment piled up against the rings apparently created by crabs. The observed biogenic sediment movement and lack of change of heading, roll, or pitch of the mine suggest the movement of sand was unassociated with physical processes. The low sea states observed, and weak bottom currents measured with an RDI ADCP, during the deployment period support this conclusion.

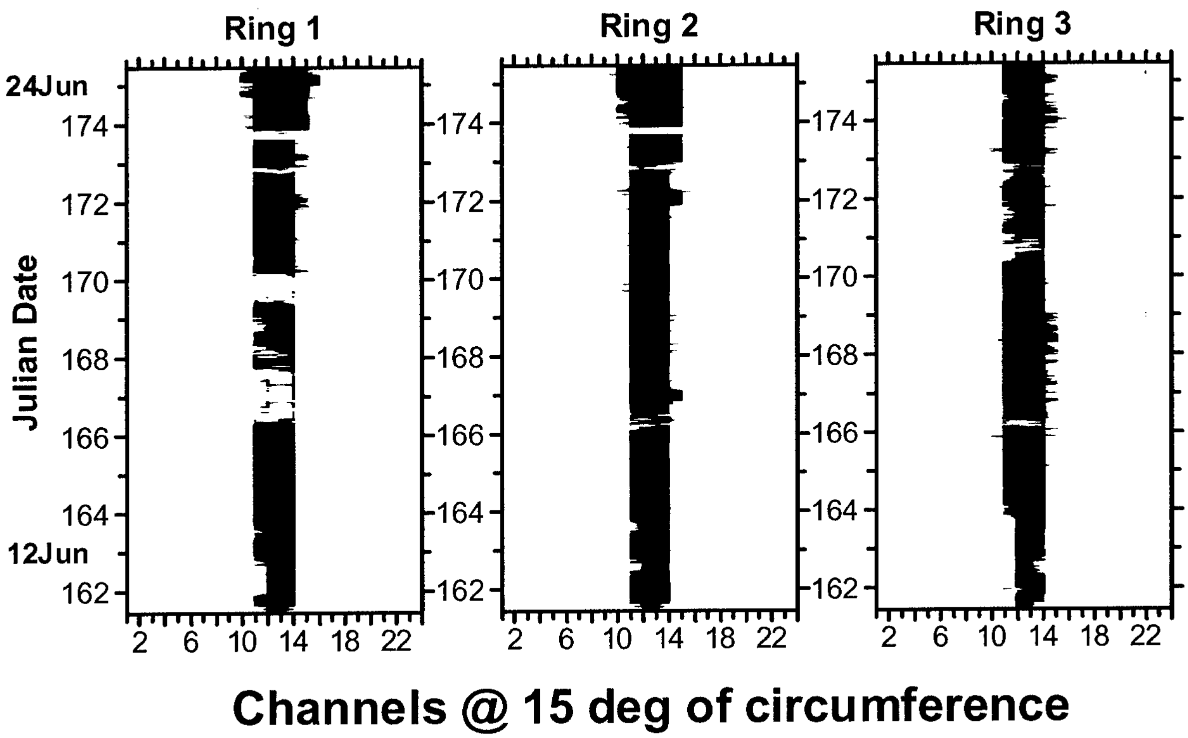

Figure 3. Mine burial measured at a shallow water (7 m) site 150 m off the beach at Panama City, Florida. The shaded areas represent a blocked passage of light between pairs of optical sensors that are located every 15° on three rings around the instrumented mine (see Figure 2).

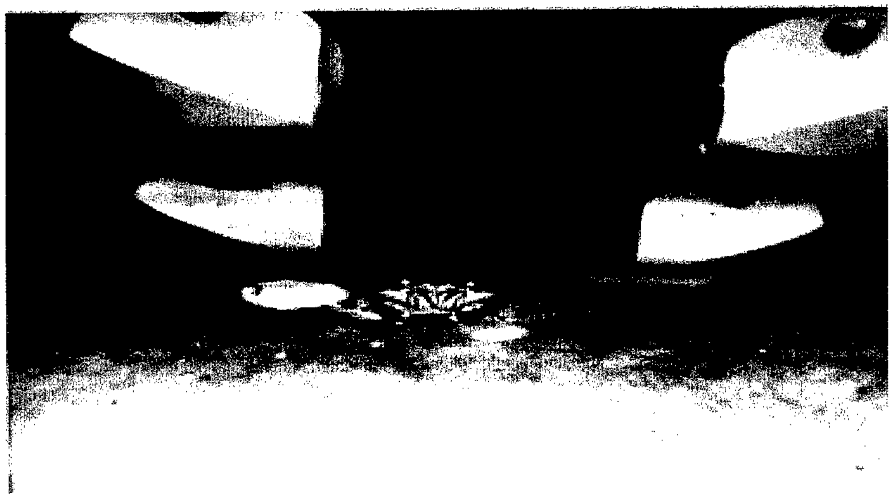

Figure 4. A Blue Crab is protecting its territory from scuba divers. The crab and fish scour the seafloor and create mounds around the instrumented mine at the Panama City site giving the appearance of burial and unburial on the optical sensors (Photograph by Ricky Ray).

Scripps Pier: A second set of experiments was conducted off the Scripps Pier in 8-m water depth from 25 July to 19 September. Sediments were well-sorted fine sand (0.19 mm mean diameter). Initially there was some burial of the mine followed by scour around both the end ring (Ring 1) and the middle ring (Ring 2) between the 3rd and 6th days after deployment (Julian dates 211-214) (Fig. 6). Seven days into the deployment (Julian date 215) onshore-directed sand movement began and rings 1 and 2 were buried (up to sensors 9-20) by the 17th day (Julian date 225). More sensor pairs on the seaward side (sensor pairs 13-24) than on the shoreward side (sensor pairs 1-12) of the mine are obstructed indicating burial predominantly on the seaward side (Fig. 5), thus supporting a shoreward bedform migration as the burial mechanism. The maximum burial included sensor pairs in an arc of 180°, equivalent to 50% burial. After the 35th day (Julian date 243) the mine began to uncover and did not approach 50% burial until the 53rd day (Julian date 261), near the time of recovery. The flat end of the mine (Ring 3) did not bury much (up to sensor pairs 13-17, or 10% burial) and was the site of bed armoring resulting from winnowing of sand and scavenging of cobble-sized gravel (Fig. 5).

The orientation of the mine changed slightly, first in response to local topography, and then on the 23rd day in response to a shift in shoaling wave direction. The waves changed to a slightly more southerly direction resulting in only a 1° counterclockwise (CCW) shift in the mine's orientation. Changes in roll and pitch due to changes in wave direction were minimal (2-3°). The rate of burial of the NRL mine will be compared to predictions by Scott Jenkins and Doug Inman (Scripps Institution of Oceanography) of a) near-field burial by sediment transport by vortices shed from the mine shape (vortex lattice method) and b) far-field burial and exposure by changes

in beach profiles due to accretion and erosion. Wave energy, period, and direction were measured both at the end of the Scripps pier and by a directional wave rider buoy west of the pier in 180 m water depth.

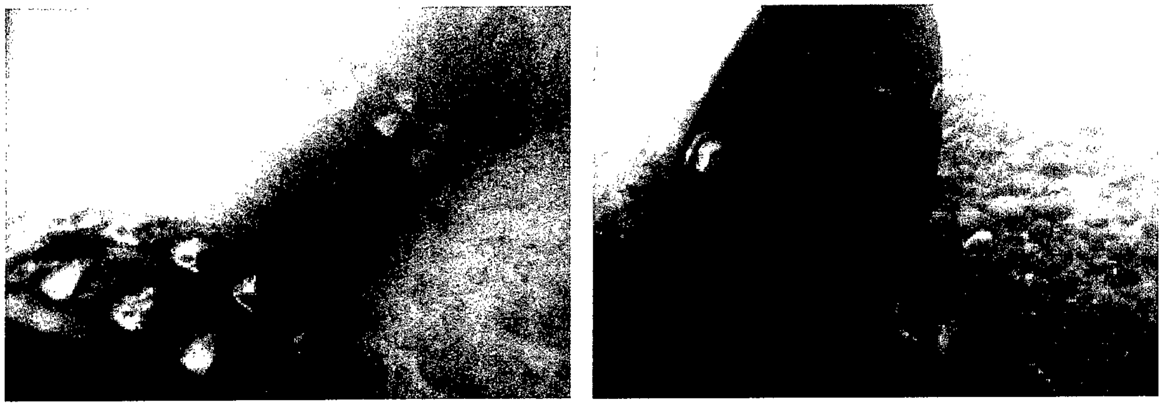

Figure 5. Scour and infilling as result of changes in direction of incoming waves (left) and bed armoring (right) around the instrumented mine (see ring 3 in figure 6) during deployment off the instrumented mine in 8-m water depth off the Scripps Pier (Photographs by Scott Jenkins)

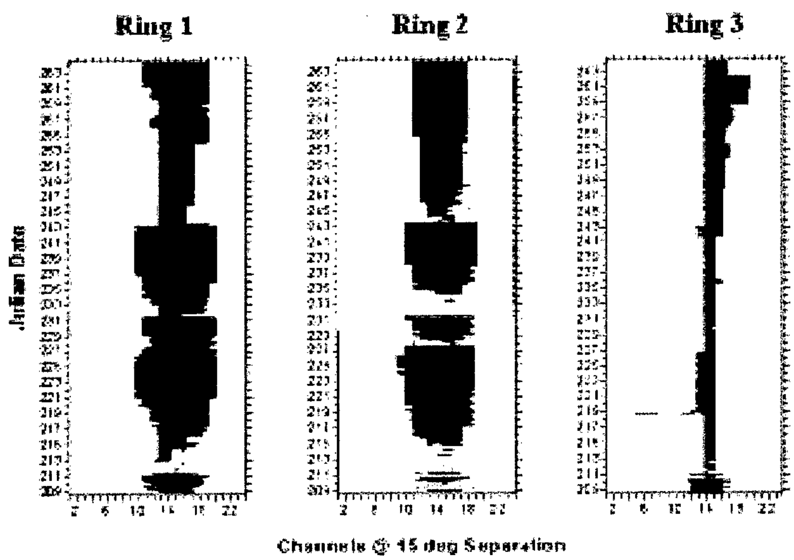

Figure 6. Mine burial measured at a shallow water (8 m) site 5m off the Scripps Pier, San Diego California. The shaded areas represent a blocked passage of light between pairs of optical sensors that are located every 15° on three rings around the instrumented mine (see Figure 2).

East Pass (Destin Florida): A mine burial experiment was conducted in East Pass, Destin Florida during October 1999. The tidal pass is the only direct entrance between the Gulf of Mexico and Choctawhatchee Bay and the seafloor is characterized by migrating sand dunes (Wright et al., 1972; Morang, 1992). A series of active dunes were located west of the navigation channel and south of the Destin Bridge using echo sounding. Divers, with the aid of lift bags, placed the mine 1 meter in the path of a migrating dune, in 4 meters water depth (Fig. 8). In response to the alternating tidal flow, the mine almost immediately (within 8 hours after deployment) rotated into the current (heading changed from 175° to 160°), rolled clockwise 4°, and flat end pitched down 4.5°. After 4-5 days the migrating face of the dune had reached the first ring and the mine was completely covered after 11 days (Fig. 9). The mine remained covered for the duration of the experiment (18 more days).

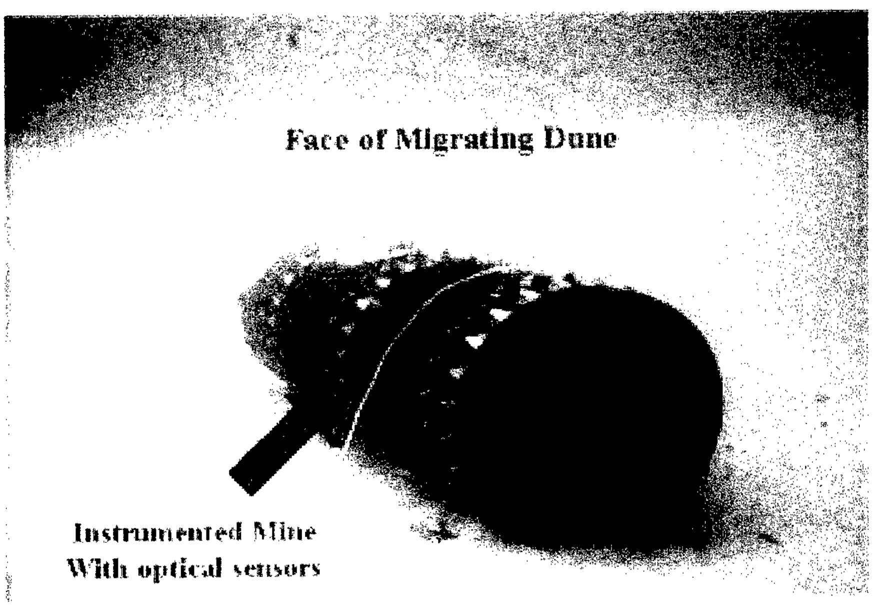

Figure 7. Instrumented mine at the beginning of experiments at East Pass, Destin Inlet, northeastern Gulf of Mexico. The face of a migrating subaqueous dune is evident in the background. The dune face is 0.60 to 0.80 m in height and is migrating towards the mine.

Sediments in East Pass were medium, well-sorted sands (0.49 mm mean grain size) with 37% porosity and 2060 kg m^{-3} bulk density. Tidal currents during the experiments were typical of East Pass (Morang, 1992) with stronger ebb than flood tides (Fig. 9). Morang (1992) attributes the comparatively long duration and high velocity flood tide to hydraulic amplification from freshwater inputs into Choctawhatchee Bay from rain and river runoff. The threshold of sediment

motion (calculated from the water depth and sediment type) is exceeded on both ebb and flood (Fig. 10) suggesting alternating seaward and bay-ward movement of the dune face, with the seaward migration dominant as a result of the longer duration and higher velocity of the ebb tide. This alternating seaward and bay-ward dune migration is evident on all three rings of the mine (Fig. 9), where both dune migration and scour contribute to covering and exposure of the optical sensors.

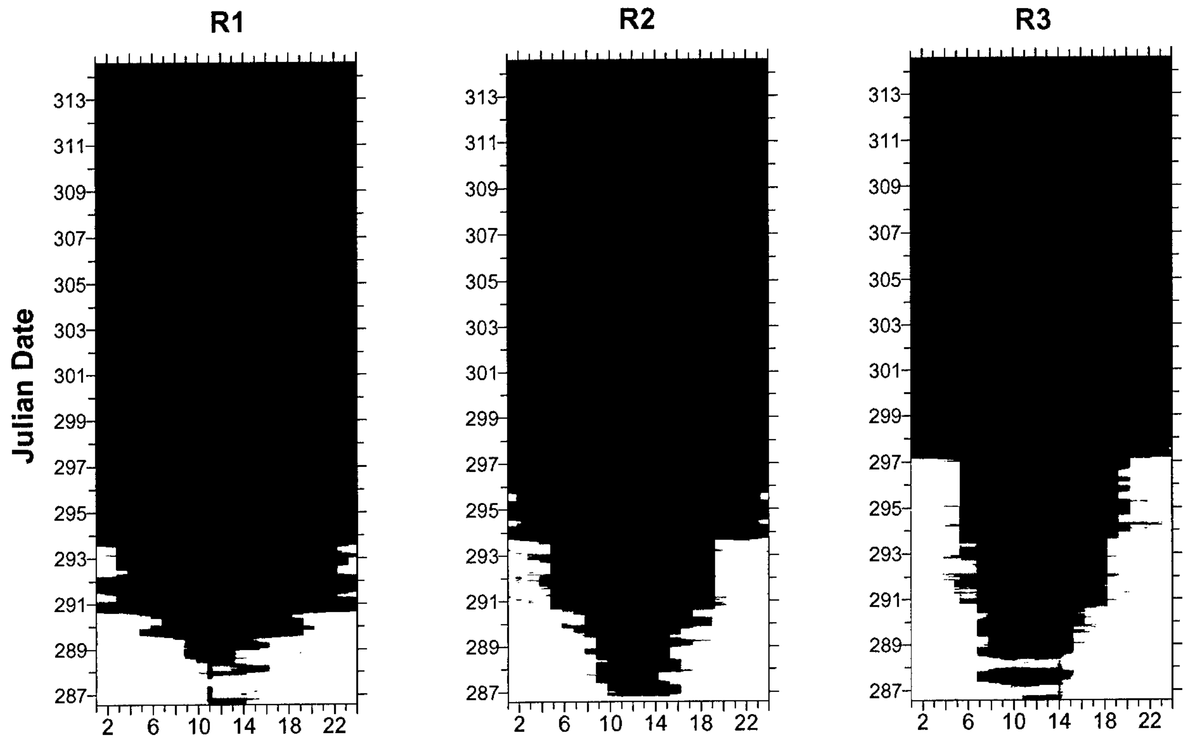

Figure 8. Mine burial measured at shallow water (4 m) site within East Pass, Florida. The shaded areas represent a blocked passage of light between pairs of optical sensors that are located every 15° on three rings (R1-R3) around the instrumented mine (see Figure 2). Note the order of burial of the three rings of optical sensors. Ring 1 was closest to the face of migrating dune.

The threshold of sediment motion for sand with a mean grain size of 0.49 mm at 4-m water depth is approximately 0.4 m s^{-1}, which was exceeded during virtually every tidal ebb and flow (Fig. 10). The average time for initial burial of a mine or the steady-state percentage burial of mines in this portion of East Pass can be calculated from the migration rate and shape of the dunes and the dimensions of the mines. Sand dune length and height were 30 m and 0.6 to 0.8 m, respectively, with a migration speed of 0.3 m d^{-1}. The average time for initial burial of mines randomly placed in East Pass is therefore 50 days and the percentage of fully buried mines after 100 days ranges between 30-70% depending on the value of the dune height. The dune dimensions (height and length) can also be estimated from water depths and bed shear stress (based on sediment mean grain size, water depth, and current speeds) and the migration rate of the dunes can be estimated from the dune shape and rates of bedload transport. Rates of bedload transport vary by as much as a factor of 4, depending which transport formula is used (Soulsby, 1997).

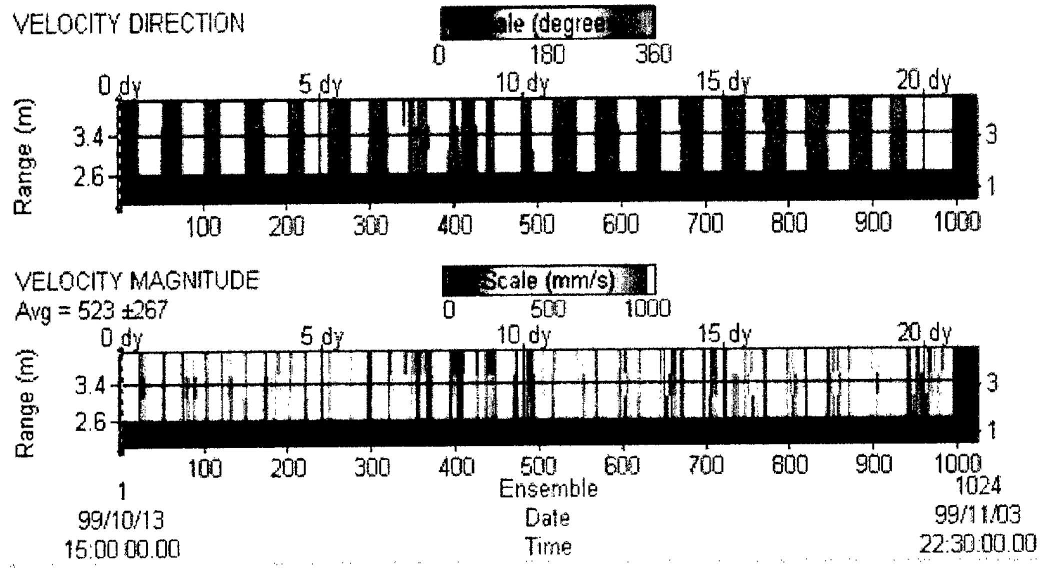

Figure 9. Speed and direction of tidal currents in East Pass, Florida measured 18 m south of the instrument mine using an RDI Acoustic Doppler Current Meter (ADCP). Current direction was predominately 330° during flood and 150° during ebb flow.

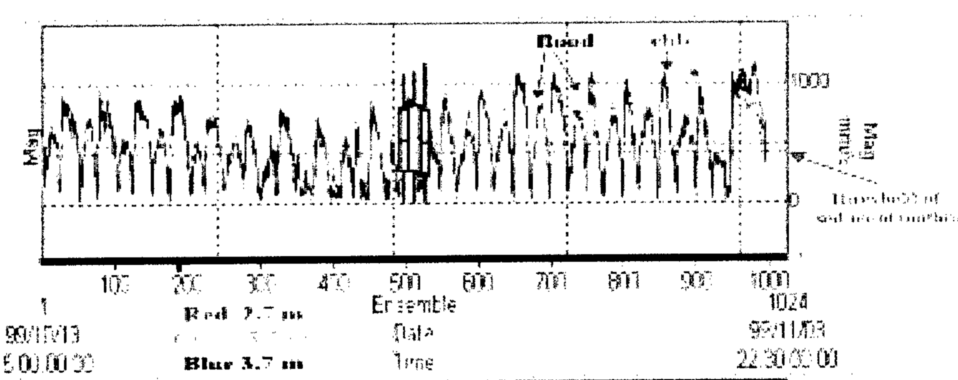

Figure 10. The speed of tidal currents in East Pass Inlet, Florida (see Figure 9). The threshold of sediment motion is exceeded during both ebb and flood tides.

BuryDuck (Duck, North Carolina): Burial experiments were conducted in 4.5-m water depths about 50-m north of the U.S. Army Corps of Engineers Field Research Facility (FRF) at Duck, North Carolina during 5-16 May 2000. The intent of these experiments was to test equipment and deployment strategies for future mine burial experiments on scour, liquefaction, and changes in beach morphology. May is the start of the relatively low-energy summer period at Duck where storms with significant wave heights greater than 2 meters are rare and little burial or changes in beach morphology are expected. The CRAB, a three-wheel mobile crane, was used to deploy the instrumented mine, several other mine shapes, two ADCPs, and a sensor package containing shear wave sensors and pressure sensors. All systems were autonomous except for the shear wave-pressure sensor package that was hard-wired to a van on the Duck pier. Divers collected cores for physical property measurements. Meteorological conditions, currents, waves, tides, and water properties are monitored routinely by the US Army Corps of Engineers at Duck (see Baron et al., for a summary of FRF data).

During the experiments winds were typically 4-9 m s^{-1} from the southwest (offshore) with two short periods of onshore winds during 11-12 May and 14-15 May (Baron et al, 2000). Significant wave heights ranged from 0.17-0.50 meters with a 24-hour period with waves of significant heights greater than 1 meter (15 May). Had we waited until the end of the May, considerable mine burial could have been expected as strong onshore winds generated waves with significant heights greater than 3 meters. Bottom currents at 1.0-m from the seafloor (60 second time intervals at ~ 9Hz) measured with our bottom-mounted ADCP show considerable variability with peak speeds between 20-30 cm s^{-1}. The highest bottom currents (>45 cm s^{-1}) were associated with the period of onshore winds and highest surface gravity waves (15 May). Tides ranged between 0.8 and 1.4 meters. At the beginning of the experiment, sediments were well-sorted, fine sands (0.177 mm mean grain size; 90% of the grains by weight between 0.1 and 0.25 mm) with 39% porosity and 2061 kg m^{-3} bulk density.

It was unfortunate that the mine's optical sensors shorted out shortly after deployment but the accelerometer data allowed tracking of the mine movement during the 10 day deployment period (5-16 May 2000). The mine changed heading from east towards north 15°, rolled counterclockwise 4°, and the beveled end pitched down 4° then up 4° almost immediately after deployment (Figure 11). The mine position remained stable until the beginning of the onshore winds (14 May) when the mine began to pitch slightly. On the 15 May, at the height of the onshore winds, with significant wave heights greater than 1 m and currents exceeding 45 cm s^{-1}, the mine pitched forward then back for a total movement of 8°, changed heading 15° through north towards the west, and rolled counterclockwise 8°. These movements are consistent with the mine rolling into a scour pit created by the mine-wave-current interactions. The beach slope between the inshore and offshore bars changed very little between bathymetric surveys on 2 and 23 May 2000 (Baron et al., 2000) suggesting morphological changes did not contribute to mine movement or burial. Given the sediment grain sizes between 0.10 to 0.25 mm, and in water depths of 3-4 m, currents greater than 37 cm s^{-1} or significant wave heights greater than 0.15 to 0.25 meters are sufficient to move sediment, create sand ripples, and certainly scour around mines where the turbulent flows are accelerated due to the mine presence. At the peak wave height (1.5 m) and bottom currents (45 cm s^{-1}) significant sediment transport and scour should be expected.

Bottom pressure fluctuations (due to surface gravity waves) and shear wave speed through the sediment were highly correlated during the entire experiments (Figure 12). The changes in shear wave speed suggest waves influence effective stresses within the sediments. When liquefied the sediments have no inherent strength and sediment shear wave speed should equal 0 (i.e., shear wave will not propagate). Shear wave speed ranged between 80-110 m s^{-1} during the experiments with the greatest fluctuations occurring during the periods of highest waves. These data suggest that shear wave may provide a useful measure of sediment liquefaction. Future experiment will couple measurements of pore pressure, shear wave speed and near bottom pressure fluctuations in order to test liquefaction burial models.

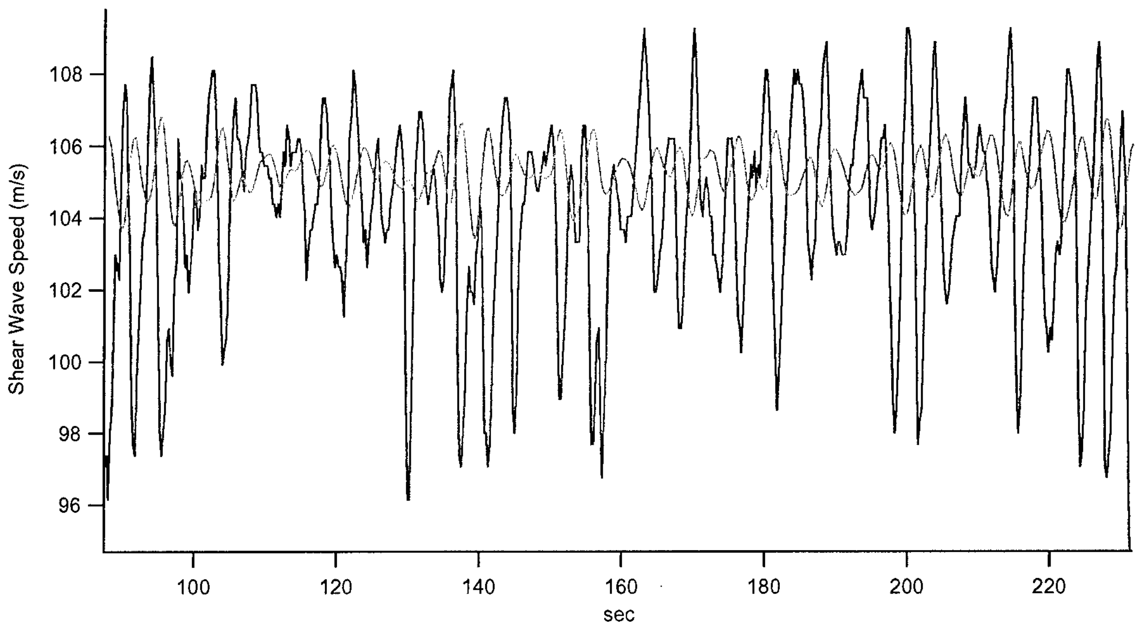

Figure 12. Temporal fluctuations of shear wave speed (red) and bottom pressure (green) during the BuryDuck experiments. Shear wave speed is in m/s and pressure measurements are not calibrated. Shear wave speeds fluctuated at the same frequency as bottom pressure but maximum shear wave speeds are 4-6 seconds before maximum bottom pressure.

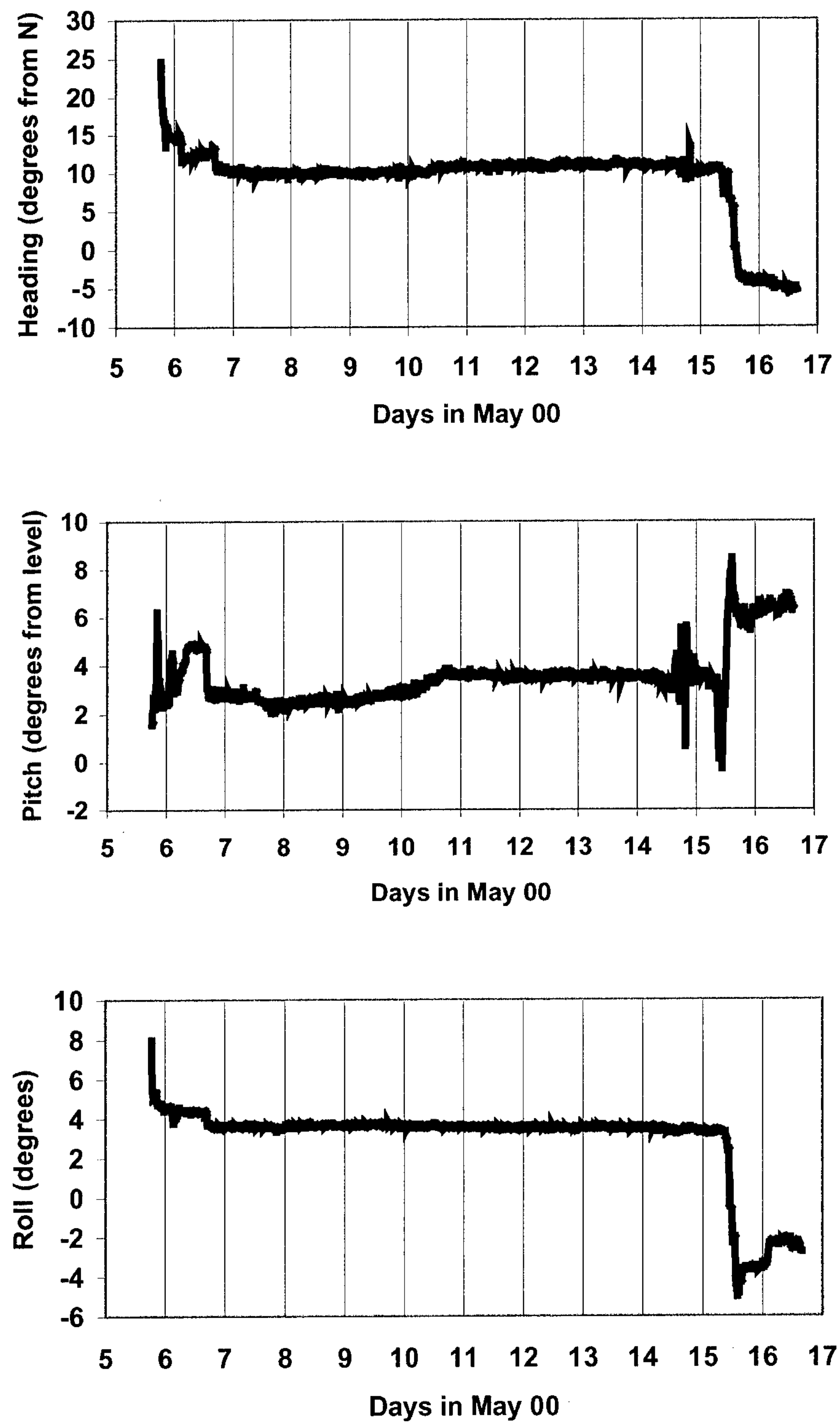

Figure 11. Motion including changes in heading, roll and pitch for the instrumented mine deployed on a sandy seafloor in 3.5 m water depth near the Duck pier 5-16 May.

Impact Burial (Mississippi Sound, Mississippi and East Bay, Louisiana): We conducted impact burial tests at two sites: 17 test drops in 4-m water depth in the Mississippi Sound (20, 25-26 September 2000) and 16 test drops in 11-12 m water depth in East Bay, just south of the East Pass outlet of the Mississippi River (2-4 November, 2000). Both sites were chosen to maximize the potential for impact burial; therefore, sediments were mostly fine-grained silts and clays with low bulk densities, and low shear strengths. The objectives of these experiments were to better understand the mine free-fall and impact dynamics to be measured and to identify inadequacies in our data acquisition concept. Divers measured mine burial within 10 minutes of impact with the seafloor using both visual and tactile methods. Sediments, collected with gravity corers, were used to measure profiles of sediment density and undrained shear strength, the two sediment inputs to the IBPM, as well as characterize sediment mean grain size. A Seabed Terminal Impact Newton Gradiometer (STING) and Expendable Bottom Profiler (XBP) were used to measure sediment undrained shear strength remotely.

The sensor package and data acquisition system of the NRL instrumented mine shape are optimized, by design, for measuring long-term (hours to months) burial in cohesionless sediments including burial by scour, liquefaction, and sand dune migration. To record short-term (microseconds to seconds) dynamics of a cylindrical shape in free-fall within the air and water column and subsequent penetration into soft cohesive sediments, the data acquisition system was reprogrammed to sample at 300 Hz and to sample only the 4-g and 25-g accelerometers. This made possible integration of deceleration data to yield reliable description of velocity and displacement of the mine shape as it falls through the water column and embeds in the seafloor. Unfortunately, increasing the data-sampling rate precluded reliable sampling of the existing magnetic compass and roll sensors. The omission of sensors to describe pitch, yaw and roll of the mine shape limits usefulness of our existing data sets: this deficiency is being corrected for future tests (see next section).

Sediments at the Mississippi Sound experimental site were a mixture of sand-, silt- and clay-sized particles (mean grain size 6 phi or 0.015 mm). Porosity (~74%) and bulk density (~1440 kg m^{-3}) varied little with depth. Shear strength, measured in the laboratory, ranged between 1-7 kPa with a general linear increase with depth, from near 2 kPa at the surface to 5-7 kPa at 2 m depth below the seafloor. Sediments at the East Bay experimental site were primarily silty-clays with mean grain sizes ranging from 8-9 phi (0.002–0.004 mm). Porosity (~70%) and bulk density (~1500 kg m^{-3}) were typical for fine-grained sediments with little obvious gradient with depth below the seafloor. Trawl fishing by shrimpers, occurring before and during the time of sampling, often mixed and resuspended these fine-grained sediments in East Bay. Shear strength, measured in the laboratory, ranged between 1-6 kPa (mean 3.5 kPa) with a tendency to increase with depth.

The Mississippi Sound experiment, in 4 m water depth, was aimed primarily at establishing the robustness of the mine impact sensor and data acquisition system. In this experiment, the mine center of mass (CM) was located at its center of volume (CV). The mine was released from horizontal, vertical nose down, and inclined 45° nose down orientations from elevations 0.3 m below the water surface (to uppermost surface of mine) to 1.0 m above the water surface (to lowest surface of mine). In all tests the mine was released with the nose chamfer facing down

(see Figure 2). According to divers, the mine was embedded 70-100% in the mud and in near horizontal orientation for 16 of the 17 drop tests. This required that the min rotate to near horizontal while traversing the 4 m water column. The divers also noted that mines released from horizontal orientation ended up slightly nose down in the mud, whereas those released from vertical or inclined, nose down, were found slightly nose up, indicating that the latter mines impacted in the mud while still in the process of rotating to a near horizontal orientation. In the 17^{th} drop test, the mine was released from vertical orientation, nose down, and only 2.7-m above the mudline. The mine was found embedded in the mud at about 45° to horizontal, indicating the fall distance was not sufficient for the mine to complete rotation to horizontal. We note that this rapid rotation to horizontal orientation is likely aided considerably by the half-face chamfer on the nose of our U.S. Mk-52 analog.

The East Bay experiments, in 12 m water depth, were aimed at testing the adequacy of paired accelerometers data for quantifying mine fall in the water column and embedment of the mine into the seafloor. The lateral excursion of the mine during fall was also measured. For this test series, weights internal to the mine were moved to shift the CM 42 mm forward of the CV, which more closely model mass distribution of the Mk-52. To measure the lateral traverse, we used a streamlined "dart", with tail fins, which fell vertically through the water column in tank tests. The bearing and distance from the dart to the mine was noted before mine release. The dart was released about 1 s ahead of the mine and the bearing and distance from dart to mine was measured by divers at the seafloor. Divers noted that the mine traversed up to 6 m horizontally during fall through the 12 m water column. Further, they noted that, for every drop, our mine rolled counterclockwise 60° - 105° (viewed from the tail) about its long axis and rotated in heading counterclockwise (viewed from the top) by up to 240°. Laboratory testing showed that the CM of the mine was slightly to the left of axis, accounting for the preference for counterclockwise roll. Once roll about the long axis begins, the change in orientation of the chamfer increases forcing for that roll motion and provides additional forcing for the observed counterclockwise rotation in the horizontal plane.

Our two impact burial data sets, gathered to date, do confirm our initial reservations regarding the IBPM description of mine motion in the water column. Figure 13 presents data from two 3-axis accelerometers mounted in the nose (Fig 13a) and tail (Fig 13b) of the instrumented mine. The mine was oriented with its long axis (z-axis) vertical and released from just below the water surface in 12-m water depth over a soft mud seafloor. The acceleration of gravity has not been processed out of the data sets presented. Time zero marks the instant of mine release. In the vicinity of 2 s into the water column fall, the z-axis acceleration drops off and the x-axis acceleration ramps up to greater than 1-g. These trends in the data indicate the completion a long-axis rotation of the instrumented mine from vertical to horizontal, which is contrary to predictions of the IBPM. The trends also indicate mine deceleration with increased drag as the projected area in the direction of travel changes from the end area of the cylinder to the projected side area. The instrumented mine shape rotated to this near horizontal orientation during fall in the water column with the center of mass (CM) of the mine located 42 mm noseward of the center of volume (CV). The greater area under the deceleration curve in vicinity of 2 s for the tail accelerometer (Fig 13b) as compared to the nose accelerometer (Fig 13a) illustrates the greater drag force applied to the tail in arresting the rotation as the z-axis approaches horizontal. The

deceleration peak in the x-axis data at 3.4-to-3.7 s marks the embedment event into the mud seafloor.

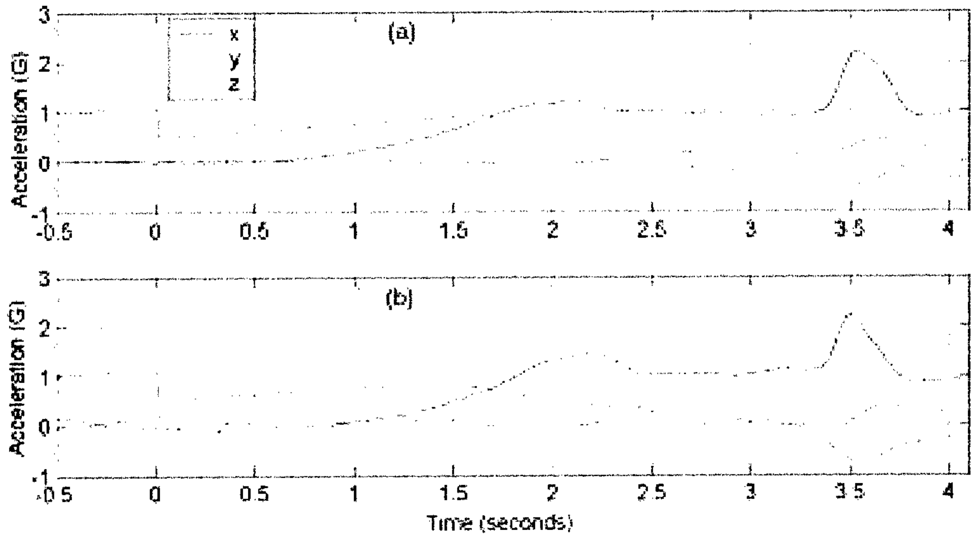

Figure 13 Impact burial test, 14 m water depth. Accelerometer data illustrating reorientation of cylindrical shape to stable orientation of long axis horizontal: (a) 3-axis, 4-g accelerometer in nose, and (b) 3-axis 4-g accelerometer in tail. Starting orientation long axis vertical, mine nose (chamfered end) down, and tail 0.3 m below water surface. Mine release at 0 sec; rotation to horizontal, 1-2 sec; and embedment in mud, 3.4-3.7 sec.

Figure 14 presents data from another test drop in which the mine was released from just below the water surface, but for this drop the mine was released from a horizontal, or z-axis horizontal, orientation. For this release condition, the mine is seen to continue in a near-horizontal orientation through embedment into the mud seafloor. The mine rotates counterclockwise about its z-axis, as indicated by the shift in acceleration magnitudes measured on the x- and y-axes. The shift is due to the changing influence of gravity on the 3-axis accelerometer as the mine rotated through 60° about the z-axis (rotation magnitudes were measured by divers before recovering the mine). The mine exhibits significant dynamics (wobble motion?) on the y-axis accelerometers in the water column between 1.5- and 3.3-s: the impact of these dynamics on the mine orientation, terminal velocity and kinetic energy causing embedment in the seafloor will be evaluated.

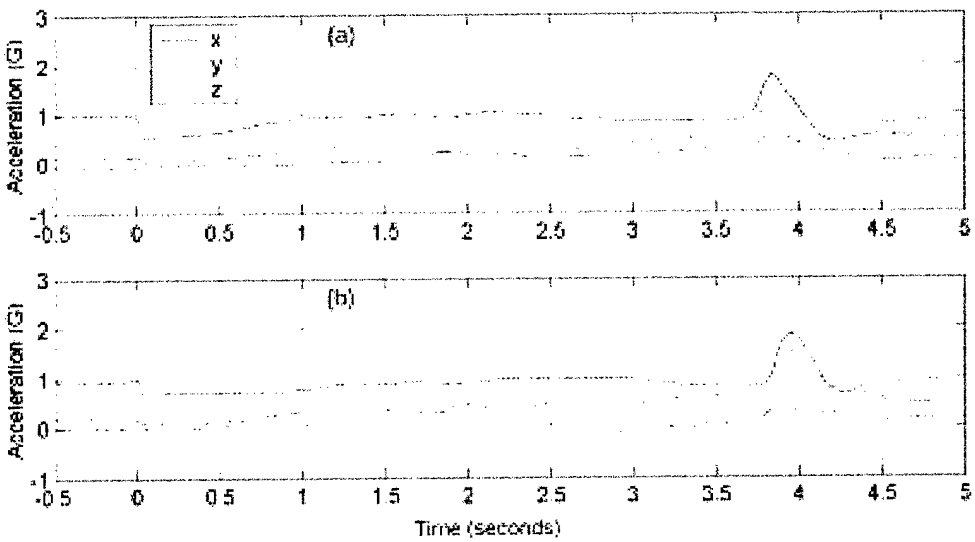

Figure 14. Impact burial test. 14 m water depth. Accelerometer data illustrating mine shape dynamics during fall in water column, 1.5-3.3 sec: (a) 3-axis, 4-g accelerometer in nose, and (b) 3-axis, 4-g accelerometer in tail. Starting orientation long axis horizontal, and upper surface of mine 0.3 m below water surface. Mine release at 0 sec; and embedment in mud, 3.7-4.2 sec.

Figure 15 presents data from a test drop where the mine was held long-axis-horizontal and released from about 1-m above the water surface, i.e., an airdrop. The mine impacts the water surface at 0.5 s, when the 4-g accelerometer went off scale. The ramp up in deceleration is believed to record mine fall in the water column before the water closes over the top of the mine. The oscillations in deceleration from 1.0-to-1.4 s may result from oscillations of the air bubble(s) trapped in the water column with closure of the water surface above the mine. This test drop was conducted in 4-m water depth: the deceleration event from 1.4-to-1.8 s marks embedment of the mine in the soft mud seafloor.

Test runs of a recent version of the IBPM, IMPACT25, suggest a deviation (our observations) from expected performance (model predictions) for cylindrical bodies falling through the water column. In short, the IMPACT25 predicts that a cylindrical shape dropped with its long-axis oriented vertical into the water will continue to fall through the water in that orientation and impact the mudline, still in that vertical orientation. From our observations an object can quite rapidly re-orient with long axis approaching horizontal, save for cylinders that are very nose or tail heavy. Thus the IBPM is suspected to inadequately describe the physics of object fall in the water column, thus throwing into question the mine velocities being calculated for the water column, and the kinetic energy then being used to calculate penetration below the mudline.

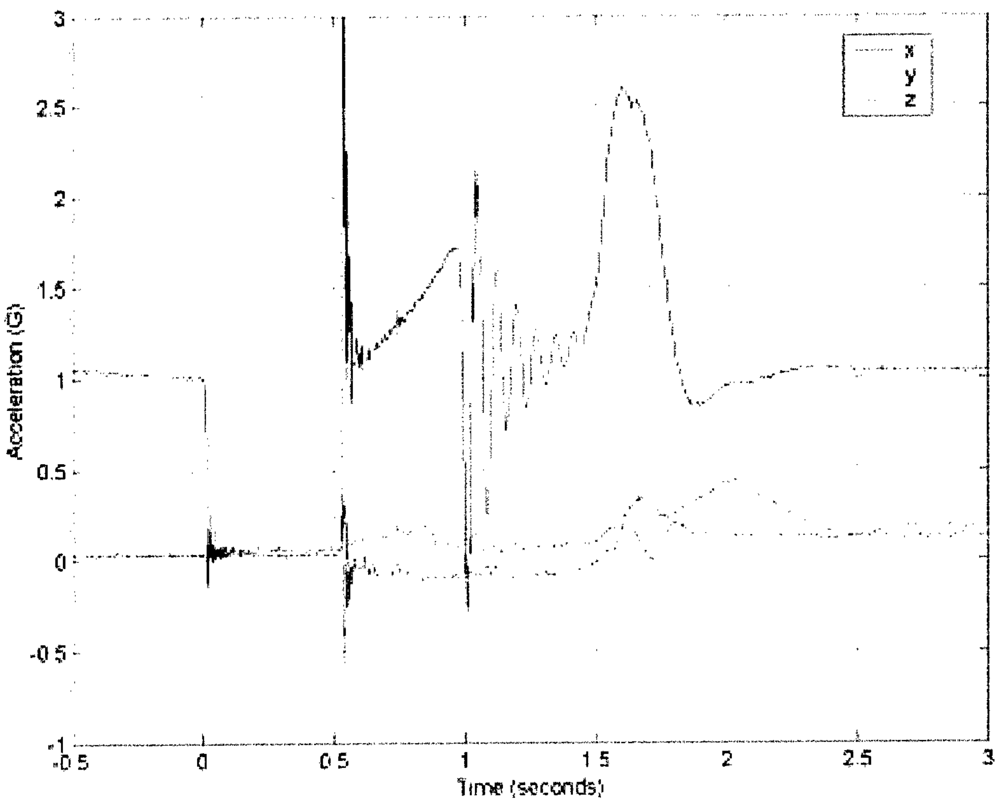

Figure 15. Impact burial test. 4 m water depth. Accelerometer data illustrating dynamics of water entry for mine shape starting long axis horizontal, released from 1 m above water surface. 4-g accelerometer at center of volume of shape. Mine release at 0 sec; impact on water, 0.5 sec; fall prior to water closure over shape 0.5-1.0 sec; shape responding to oscillation of trapped air bubble(s), 1.0-1.4 sec; and embedment in mud, 1.4-1.8 sec.

Towards a New Generation of Instrumented mines

These experiments provide a test of some of the measurement systems to be used for experiments planned by NRL and the Office of Naval Research (ONR) in 2001-2002. In order to carry out these experiments a new generation of more capable instrumented mines is being developed and will be discussed below. The results presented here should therefore be considered both preliminary and serendipitous to the ultimate objectives of the "Mine Burial Process" program being conducted at NRL and ONR. A more detailed evaluation of the results and a comparison to predictions from the current group of mine burial prediction models is underway and will be presented later.

Omni Technologies, Inc. has recently been awarded a Phase II SBIR contract to design and build an improved instrumented mine based, in part, on the results of these experiments. The new-instrumented mines will be constructed of bronze rather than aluminum and contain a variety of sensors to detect mine burial and to sense the environmental processes responsible for that burial.

Bronze offers numerous advantages over aluminum and provides the same non-magnetic properties. Bronze is heavier providing the desired mine weight without added material. Bronze also provides properties that exhibit reduced biologic fouling and corrosion. The material cost is higher but this is balanced by a less complex mechanical design and no need for externally applied protection such as anodizing and paint.

The new mines will use acoustic rather than optical sensors to detect burial. Although optical sensors provide simple and reliable methods to detect percent burial, they have a number of drawbacks. Optical sensors create protrusions on the mine surface that distort the hydrodynamic flow field around the mine, perhaps enhancing burial by scour. The optical protrusions are prone to damage during handing and deployments, easily fouled by biological organisms during experiments, and require two sensors per measurement, increasing the number of penetrations and probability of leaks. The new-instrumented mines will use 100 1.5- and 3.0-MHz acoustic sensors, scattered over the surface of the mine, to detect percent burial and to characterize developing scour pits and migrating sand dunes or ripples. Acoustic inversion, using data from the same acoustic sensors, will be implemented in an attempt to characterize the boundary layer flow around the mine, measure sediment concentrations and flux in the vicinity of the mine, and determine initiation of bedload transport. These techniques include time-gated acoustic backscatter strengths to determine sediment concentrations in the water column around the mine; coherent Doppler and cross-correlation velocity profiles for characterizing mean and turbulent flows around the mine; and cross correlation of time-gated backscatter strength to determine changes in bottom roughness indicative of the initiation of bedload transport (see Thorne and Taylor, 2000 and Dworski and Jackson 1994, for details).

Hydrophones will be used to measure acoustic energy impinging on the mine from search sonar. By using burial and heading information from instrumented mines in a test field, post exercise analysis can be performed to determine when, why, and under what conditions acoustic detections should have occurred. The hydrophones will also have the capability of responding to a coded pulse for system location during extraction as well as for responding to search sonar during training exercises.

As with the prototype instrumented mine, roll, pitch and azimuth sensors will be incorporated. The bronze housing allows magnetic heading sensors to be used. Additional sophistication will be implemented in the electronics and software to conserve power for extended deployments up to six months. At least five processors will be used to distribute the processing allowing only the necessary electronics to draw power for the scheduled sensor data acquisition. The multiple processor configurations also enables more capable mission planning algorithms that will provide fixed sampling modes as well as adaptive sampling modes. The adaptive sampling modes will detect events that trigger higher rate sampling sequences as long as the event is valid.

Six pressure sensors will be incorporated to monitor local sea state. Currently, an external sensor suite is used for this measurement. Knowledge of surface wave conditions is a required input to most scour and liquefaction mine burial models. These pressure sensors should also be able to detect the presence of ship wakes even in the presence of high-sea states. Plans are to have a completed instrumented mine by the first quarter of 2002 with 3 additional systems being

completed soon after. Much of the system design is completed and detailed design of the instrumentation is diligently under way.

A stand-alone removable package, deployable with a variety of mine shapes, is under development for impact burial prediction. We had initially thought that two 4-g accelerometers, one at each end of the mine, could be employed to describe roll, pitch and yaw; however, we learned from our 14-m water depth tests that roll of the mine about its long axis made extraction of those data very uncertain. To correct this deficiency, a fiber optic vertical gyro (6-degree of motion sensor) and 3-axis magnetometer (heading) will be added to the 3-axis, 4-g accelerometer instrument suite to sense roll, pitch and yaw of the mine in impact burial tests. We are also replacing the hard drive data storage with solid-state disk storage to minimize potential for damage during water surface impact. This dedicated impact burial sensor and data acquisition package will be encased in its own pressure case, about 0.23 m diameter by 0.6 m long, fitted for data download without case removal from the external mine case. The objectives for this package are to monitor mine motion across the air-water interface, through the water column (x,y,z accelerations and roll pitch and yaw), and penetration of the mine into the sediment, including determining percent mine burial. Because of concerns over potential damage to the scour burial sensors, both optical and acoustic types, we have decided to fabricate mine cases dedicated, and uniquely designed for, impact burial tests. We will begin with two bronze cylindrical cases, both about 0.53 m diameter: one about 1.7-m long and the second about 2.6-m long. Interchangeable, add-on, hemispherical and flattened round ends are planned for easy attachment and removal from the nose and/or tail of the cylindrical case to permit generic modeling of the various threat mine types. Lead weighting internal to the mine case will permit adjustment of the overall mine bulk unit weight, location of center of mass (CM), and moment of inertia about three axes. All three of these parameters are critical to mine behavior in free-fall: the location of CM dictates the degree of nose-down attitude, the CM and bulk unit weight determines the terminal fall velocity, and the moment of inertia strongly influences the rate of rotation and "wobble" in all three axes. Fabrication, assembly and testing of the sensor package, its pressure housing, and the impact burial mine cases is to be completed by July 2001. The first field application of the new-instrumented impact burial mines is planned for a 10-day experiment off Corpus Christi, Texas in October 2001. The experimental area is in 20-m water depth, well beyond depths required for the mines to come to terminal velocity, on a soft mud seafloor.

We are also considering physical model tests in a tank facility to permit rapid gathering of mine shape free-fall dynamics data via both the instrument package described earlier and high-speed photography. One drawback is that, to maintain Reynolds number similitude, the physical mine model must be fairly large, perhaps one-half scale, with bulk unit weight equal to that of the prototype. A second drawback, reported in this paper, is that we have measured horizontal traverses of our mine shape of up to one-half the water depth, which requires a relative large tank.

In future experiments with these instrumented mines we will attempt to quantify the relative importance and interactions of scour, liquefaction, and bedform alteration. The conditions under which momentary or cyclic liquefaction is a significant contributor to mine burial will be quantified and the relative importance of liquefaction as a precursor to scour will be determined. Future experiments will determine the bed stress conditions necessary to initiate sand motion in

the presence of a mine and compare rates of scour based on empirical bedload stress and transport, and finite element turbulent flow predictions. Experiments in tidally dominated environments will be used to quantify the interaction of bedform (subaqueous dunes) migration and scour and to quantify the environmental forcing functions leading to sediment transport, bedform migration and scour. Impact burial experiments should provide data required to improve prediction of the 6-degrees of motion of various mine shapes through the water column and predict their penetration into the seafloor. The overall objectives are to determine the conditions where various mine burial processes dominate; provide rigorous tests of proposed mine burial models; and ultimately develop and validate an integrated mine burial prediction model such as proposed in Figure 1.

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